Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the U.S.

CPUC Technical Workshop on Pumped Storage

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Project Summary & Team

- Project Team led by Argonne National Laboratory was awarded funding by the U.S. Department of Energy for the study**: Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the U.S.**

- Team members:
  - **Argonne National Laboratory (Argonne)** – Project Lead
  - **Siemens Energy, Inc.**
  - **Energy Exemplar, LLC.**
  - **MWH Americas, Inc.**
  - **National Renewable Energy Laboratory (NREL)**

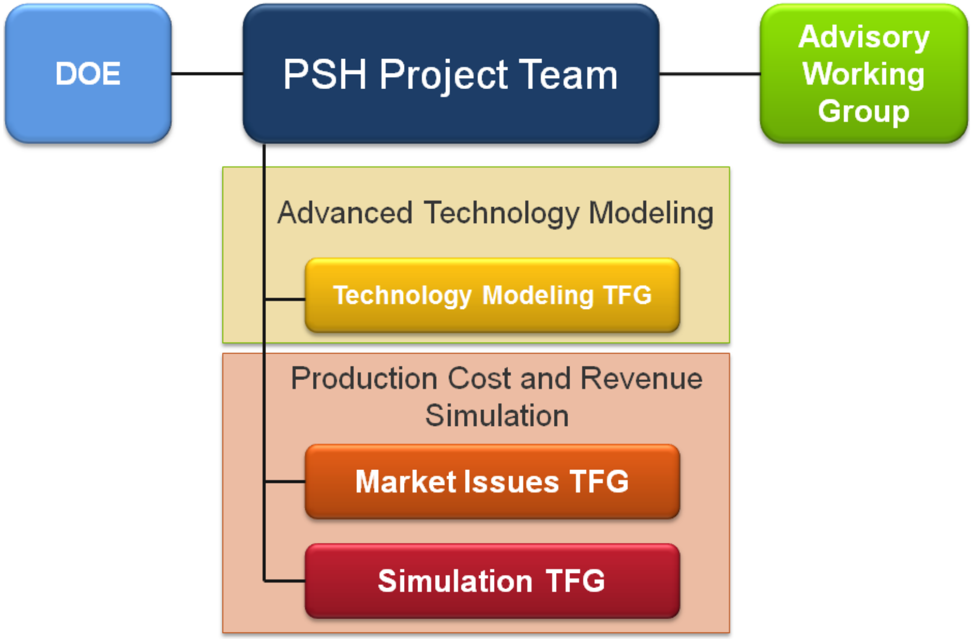
- Project website: http://www.dis.anl.gov/psh

Project Goals & Objectives

Develop detailed models of advanced PSH plants to analyze their technical capabilities to provide various grid services and to assess the value of these services under different market structures.

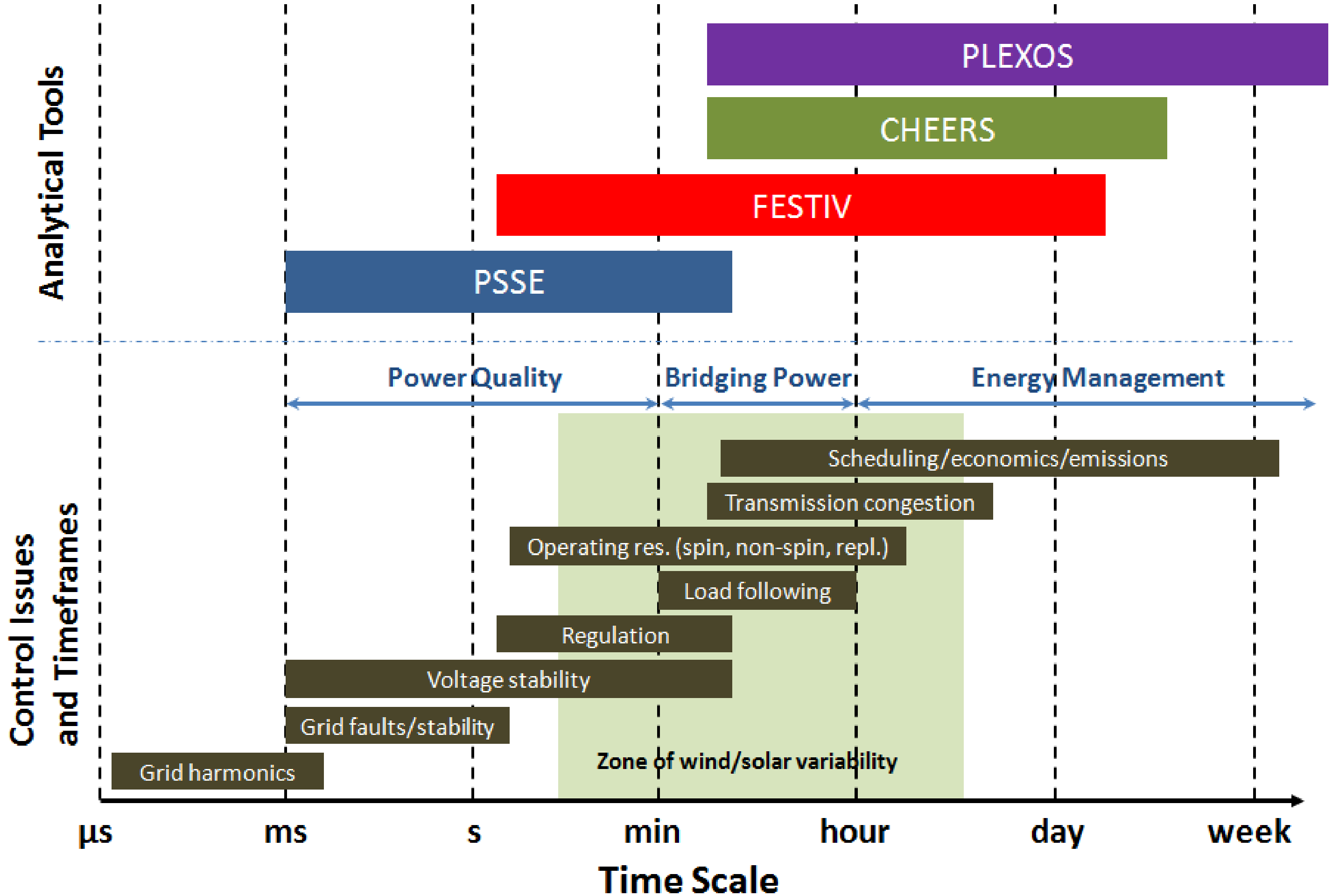
Main Objectives:

- Improve modeling representation of advanced PSH plants
- Quantify their capabilities to provide various grid services
- Analyze the value of these services under different market conditions and levels of variable renewable generation
- Provide information on full range of benefits and value of PSH



Analysis Addressed Wide Range of Control Issues & Timeframes

- Analysis aimed to capture PSH dynamic responses and operational characteristics across different timescales, from a fraction of a second to days/weeks.



Advanced Technology Modeling

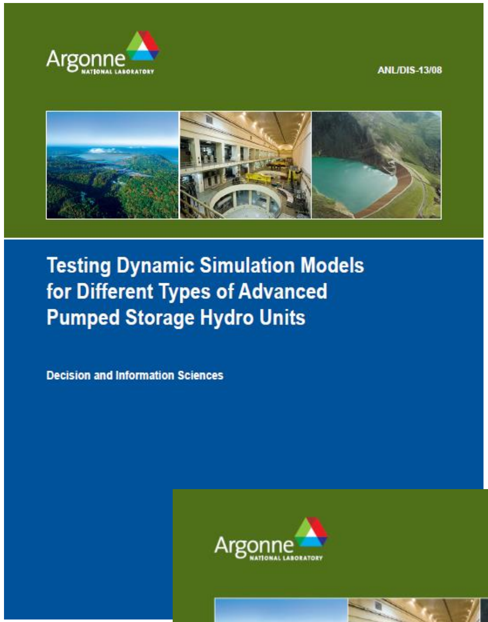
Model Development

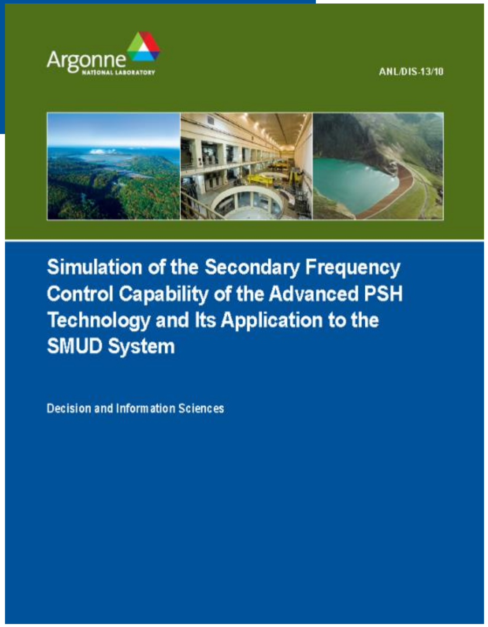
- Technology Modeling TFG has developed vendor-neutral dynamic models for advanced PSH technologies and described them in three reports:
  - ✓Review of <u>existing CH and PSH models</u> in use in the United States
  - ✓Dynamic simulation models for <u>adjustable speed PSH</u>
  - ✓Dynamic simulation models for <u>ternary PSH units</u>
- Draft models and reports were reviewed by the AWG members
- Reports have been cleared for unlimited distribution and are now publicly available.

Integration and Testing of Dynamic Models

Model Integration and Testing

- Dynamic models for adjustable speed PSH and ternary units were coded and integrated into the PSS®E model
- Testing of these models for both generating and pumping mode of operation was performed using PSS®E test cases and dynamic cases for Western Interconnection (WI)
- Additional AGC studies have been performed for SMUD balancing authority
- Published a report on frequency regulation capabilities of advanced PSH technologies



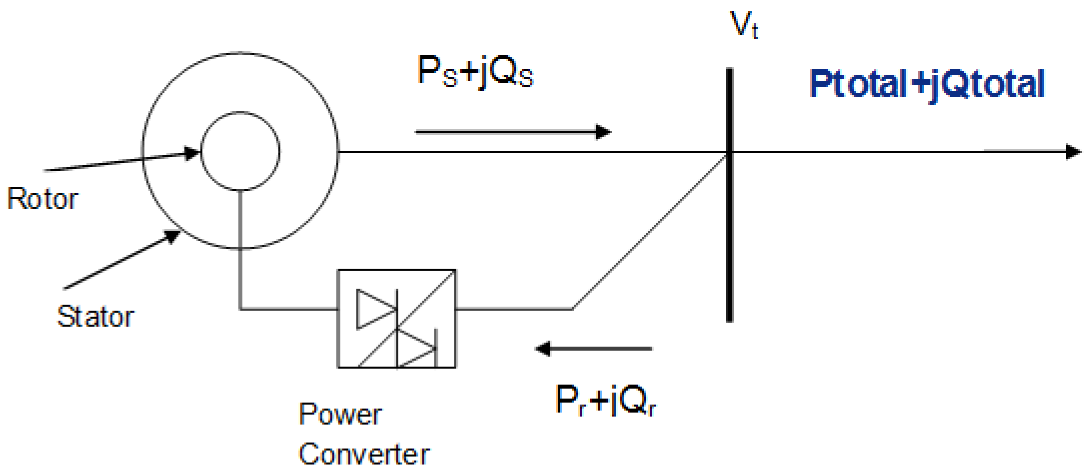


PSH Provides Various Services and Contributions to the Power System

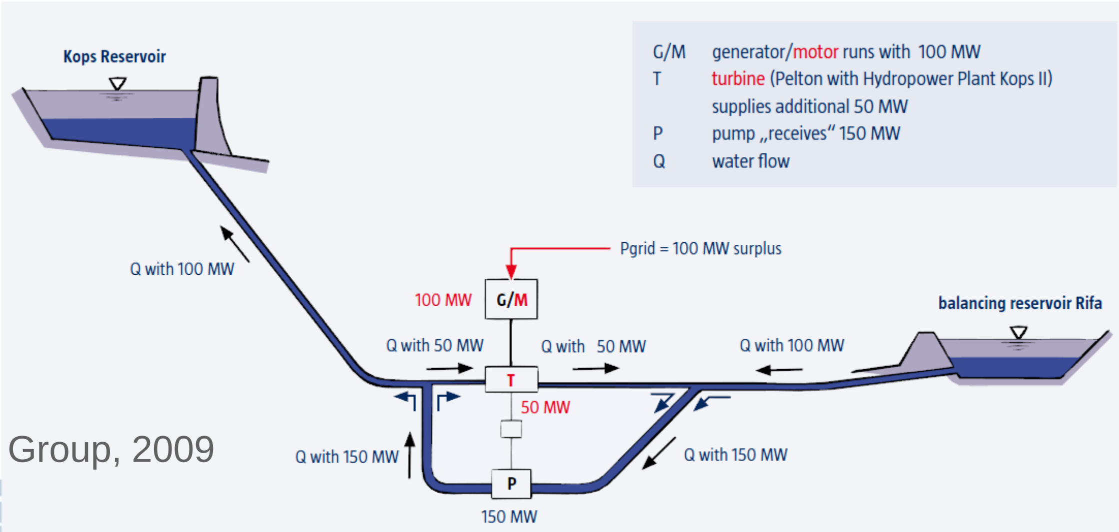
	PSH Contribution
1	Inertial response
2	Governor response, frequency response, or primary frequency control
3	Frequency regulation, regulation reserve, or secondary frequency control
4	Flexibility reserve
5	Contingency spinning reserve
6	Contingency non-spinning reserve
7	Replacement/Supplemental reserve
8	Load following
9	Load leveling / Energy arbitrage
10	Generating capacity
11	Integration of variable energy resources (VER)
12	Portfolio effects
13	Reduced cycling of thermal units
14	Reduced transmission congestion
15	Voltage support
16	Improved dynamic stability
17	Reduced environmental emissions
18	Energy security
19	Transmission deferral
20	Black start capability

Adjustable Speed PSH Technologies Provide Even More Flexibility than Conventional Fixed-Speed PSH

- Adjustable speed PSH with doubly-fed induction machines (DFIM):



- Ternary units with hydraulic short circuit:



Source: Illwerke VKW Group, 2009

Additional Benefits of Adjustable Speed PSH

- More flexible and efficient operation in generation mode
  - Minimum unit power output as low as 20%-30%
  - Increased efficiency and lifetime of the turbine at partial loads by operating at optimal speed
- Frequency regulation capabilities also available in the pumping mode
- Electronically decoupled control of active and reactive power
  - Provides more flexible voltage support
- Improved dynamic behavior and stability of power system
  - Improved transient stability in case of grid faults (e.g., short circuit faults in the transmission system)
  - Reduced frequency drops in case of generator outages
- Better compensation of variability of renewable energy sources
  - More flexible and quicker response in generating (turbine) mode
  - Variable power in pumping mode to counterbalance variability of wind
  - Excellent source of frequency regulation during the off-peak hours

PLEXOS Model was Used for Production Cost and Revenue Simulations

- Focus on western U.S. (several levels of geographical scope, including entire WI, CAISO/California, and individual balancing authority - SMUD)

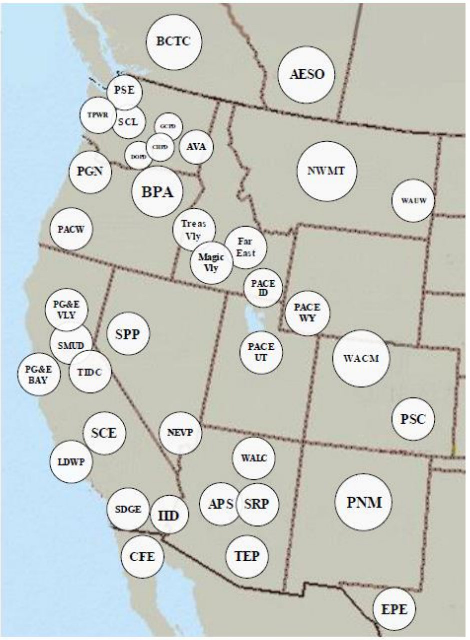
- A “future year” (FY) representation of the WI system is largely based on WECC’s long-term projections for 2022

- Simulation Period:
  - DA simulations (hourly time step) for entire year to determine maintenance schedule of thermal units and annual-level PSH economics
  - DA-HA-RT sequential simulations (hourly and 5-minute time step) for typical weeks (third week in January, April, July, and October) to analyze PSH operation under conditions of variability and uncertainty of renewable resources

PLEXOS Inputs were Based on TEPPC 2022 Common Case

- WECC's TEPPC 2022 case served as foundation for building FY cases (certain case parameters and data varied depending on scenario assumptions)
- Both cost-based and market-based approaches were used in analysis
- Two levels of variable energy resources were analyzed:
  - Base RE scenario (RPS mandate)
  - High RE scenario (High Wind from WWSIS-2)
- PLEXOS simulations of WI and California were performed at nodal (bus) level

TEPPC Load Bubbles



Legend

AESO	Alberta Electric System Operator
APS	Arizona Public Service
AVA	Avista
BCTC	British Columbia Transmission Corp
BPA	Bonneville Power Administration
CFE	Comision Federal de Electricidad
CHPD	Chelan Co PUD
DCPD	Douglas Co PUD
EPE	El Paso Electric
Far East	Far East (Idaho Power)
GCPD	Grant Co PUD
IID	Imperial Irrigation District
LDWP	Los Angeles Dept of Water & Power
Magic Vly	Magic Valley (Idaho Power)
NEVP	Nevada Power
NWMT	Northwestern Montana
PACW	PacifiCorp West
PACE ID	PacifiCorp East – Idaho
PACE UT	PacifiCorp East – Utah
PACE WY	PacifiCorp East – Wyoming
PG&E Bay	Pacific Gas & Electric Bay Area
PG&E VLY	Pacific Gas & Electric Valley Area
PGN	Portland Gen Electric
PNM	Public Service New Mexico
PSC	Public Service Colorado (Xcel)
PSE	Puget Sound Energy
SCE	Southern California Edison
SCL	Seattle City Light
SDGE	San Diego Gas & Electric
SMUD	Sacramento Municipal District
SPP	Sierra Pacific Power
SRP	Salt River Project
TEP	Tucson Electric Power
TIDC	Turlock Irrigation District
TPWR	Tacoma Power
TreasVly	Treasure Valley (Idaho Power)
WACM	Western Area Power Admin Colorado/Missouri
WALC	Western Area Power Admin Lower Colorado
WAUW	Western Area Power Admin Upper Missouri

- 39 load regions in WI
- 8 spinning reserve sharing groups
- 20 flexibility & regulation reserve sharing groups

PLEXOS Modeling of California in 2022

Simulation runs for California were performed using market-based approach (cost-based approach was applied for WI and SMUD):

California simulations:

- ***Annual runs*** for Base and High-Wind scenarios (DA runs with hourly time step and co-optimization of energy and ancillary services):
  - Without PSH plants
  - With existing conventional (fixed-speed) PSH plants in California
  - With existing FS PSH and 2 adjustable speed PSH (at Iowa Hill and Eagle Mountain locations)
- ***Weekly runs*** for four typical weeks in different seasons (January, April, July, and October) applying three-stage approach (DA-HA-RT) and co-optimization of energy and ancillary services:
  - Without PSH plants
  - With existing conventional (fixed-speed) PSH plants
  - With existing fixed-speed PSH and 2 adjustable speed PSH (at Iowa Hill and Eagle Mountain locations)

California: System Production Costs in 2022

- Baseline RE scenario:

Base Renewable Scenario	Total Generation	PSH Generation	Production Cost	Annual Cost Reduction		Annual Cost Reduction per kW of PSH Capacity	
	GWh	GWh	$ Million	$ Million	%	Total PSH MW	$/kw-year
No PSH	265,538	-	5,078	-	-	-	-
With FS PSH	267,001	2,725	4,967	111	2.18%	2626	42.10
With FS&AS PSH	269,374	5,313	4,907	171	3.36%	4425	38.60

Annual operating costs savings

- High-Wind RE scenario:

High-Wind Renewable Scenario	Total Generation	PSH Generation	Production Cost	Annual Cost Reduction		Annual Cost Reduction per kW of PSH Capacity	
	GWh	GWh	$ Million	$ Million	%	Total PSH MW	$/kw-year
No PSH	253,872	-	4,120	-	-	-	-
With FS PSH	256,069	5,299	3,934	186	4.52%	2626	70.91
With FS&AS PSH	257,018	9,456	3,745	376	9.12%	4425	84.97

Significant cost savings

California: Curtailments of RE Generation in 2022

- Baseline RE scenario:

CA Renewable Curtailment in the Base Renewable Scenario			
		Renewable Curtailment Reduction	
Case	GWh	GWh	%
No PSH	155	-	0%
With FS PSH	46	108	70%
With FS&AS PSH	14	141	91%

With additional AS PSH, curtailments of RE almost eliminated

- High-Wind RE scenario:

CA Renewable Curtailment in the High-Wind Renewable Scenario			
		Renewable Curtailment Reduction	
Case	GWh	GWh	%
No PSH	618	-	0%
With FS PSH	380	238	39%
With FS&AS PSH	275	343	55%

California: PSH Provisions of System Reserves in 2022

- Baseline RE scenario:

Base Renewable Scenario	Base - No PSH		With FS PSH		With FS&AS PSH	
	Total Req. (GWh)	PSH Provision (GWh)	Total Req. (GWh)	PSH Provision (GWh)	Total Req. (GWh)	PSH Provision (GWh)
Non-Spinning Reserve	8,505	-	8,505	7,090	8,505	7,905
Spinning Reserve	8,505	-	8,505	224	8,505	2,463
Flexibility Down	3,130	-	3,130	47	3,130	1,098
Flexibility Up	3,130	-	3,130	13	3,130	341
Regulation Down	3,810	-	3,810	171	3,810	1,264
Regulation Up	3,839	-	3,839	164	3,839	1,109

Due to AS PSH flexible pumping

- High-Wind RE scenario:

High-Wind Renewable Scenario	Base - No PSH		With FS PSH		With FS&AS PSH	
	Total Req. (GWh)	PSH Provision (GWh)	Total Req. (GWh)	PSH Provision (GWh)	Total Req. (GWh)	PSH Provision (GWh)
Non-Spinning Reserve	8,505	-	8,505	4,774	8,505	5,492
Spinning Reserve	8,505	-	8,505	247	8,505	2,022
Flexibility Down	4,804	-	4,804	141	4,804	1,934
Flexibility Up	4,804	-	4,804	26	4,804	200
Regulation Down	4,394	-	4,394	377	4,394	1,761
Regulation Up	4,442	-	4,442	144	4,442	1,201

Due to AS PSH flexible pumping

California: System Emissions in 2022

- Baseline RE scenario:

Base Renewable Scenario	CO2	NOx	SO2	Emission Reduction (ton)			Emission Reduction (%)		
	Ton	ton	ton	CO2	NOx	SO2	CO2	NOx	SO2
No PSH	65,429,529	53,681	6,006	-	-	-	0.0%	0.0%	0.0%
With FS PSH	64,741,362	53,512	6,093	688,166	170	(87)	1.1%	0.3%	-1.5%
With FS&AS PSH	64,625,964	53,568	6,165	803,565	113	(160)	1.2%	0.2%	-2.7%

- High-Wind RE scenario:

High-Wind Renewable Scenario	CO2	NOx	SO2	Emission Reduction (ton)			Emission Reduction (%)		
	Ton	ton	ton	CO2	NOx	SO2	CO2	NOx	SO2
No PSH	51,515,736	44,936	5,334	-	-	-	0.0%	0.0%	0.0%
With FS PSH	49,692,105	44,010	5,350	1,823,631	925	(16)	3.5%	2.1%	-0.3%
With FS&AS PSH	47,904,187	43,177	5,427	3,611,549	1,759	(93)	7.0%	3.9%	-1.7%

PSH plants reduce CO2 and NOx emissions under both scenarios

California: Thermal Generator Cycling in 2022

- Baseline RE scenario:

Base Renewable Scenario	Total Number of Thermal Starts	Total Thermal Start Cost	Cost Reduction	
		$ Million	$ Million	%
No PSH	18,514	56	-	-
With FS PSH	14,646	46	10	17.35%
With FS&AS PSH	12,134	36	20	35.40%

- High-Wind RE scenario:

High-Wind Renewable Scenario	Total Number of Thermal Starts	Total Thermal Start Cost	Cost Reduction	
		$ Million	$ Million	%
No PSH	17,862	54	-	-
With FS PSH	14,351	44	11	19.56%
With FS&AS PSH	11,864	35	20	36.42%

FS & AS PSH plants reduce cycling cost of thermal units by one third

California: Thermal Generator Ramping in 2022

- Baseline RE scenario:

Base Renewable Scenario	Total Thermal Generator Ramp Up	Total Thermal Generator Ramp Down	Ramp Up Reduction		Ramp Down Reduction	
	GW	GW	GW	%	GW	%
No PSH	4,273	6,603	-	-	-	-
With FS PSH	3,623	5,552	650	15.20%	1,052	15.93%
With FS&AS PSH	2,924	4,456	1,349	31.56%	2,147	32.51%

Ramping of thermal units reduced by one third

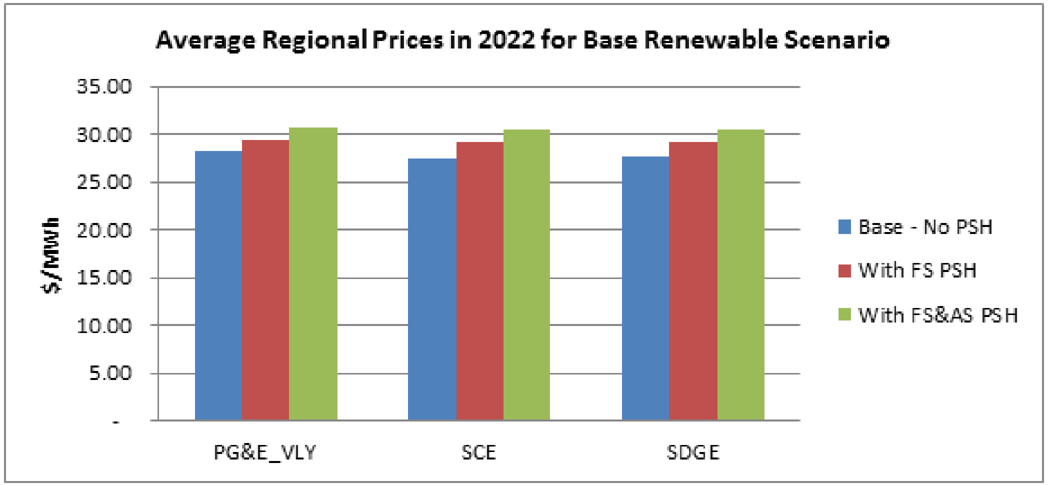
- High-Wind RE scenario:

High-Wind Renewable Scenario	Total Thermal Generator Ramp Up	Total Thermal Generator Ramp Down	Ramp Up Reduction		Ramp Down Reduction	
	GW	GW	GW	%	GW	%
No PSH	3,609	5,681	-	-	-	-
With FS PSH	3,078	4,737	531	14.71%	945	16.63%
With FS&AS PSH	2,396	3,738	1,214	33.63%	1,943	34.20%

Ramping of thermal units reduced by one third

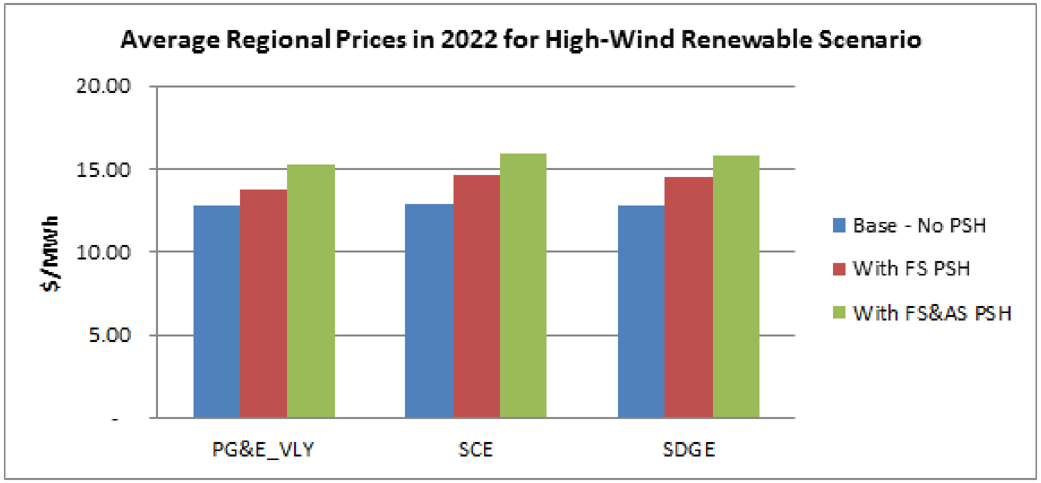
California: Regional LMPs in 2022 Are Significantly Lower under High-Wind RE Scenario

- Baseline RE scenario:



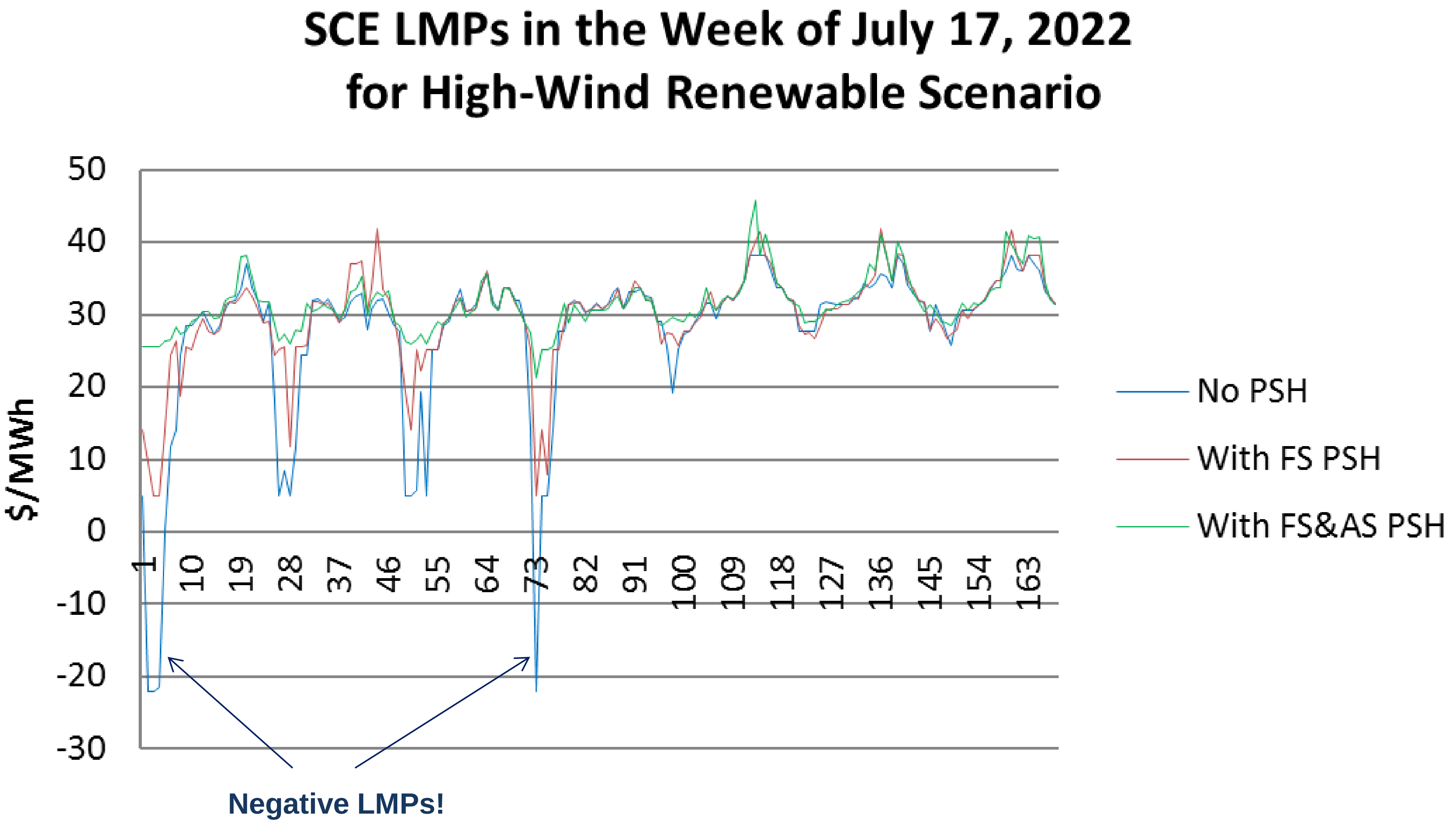
Average LMPs:
27-30 $/MWh

- High-Wind RE scenario:



Average LMPs:
13-16 $/MWh

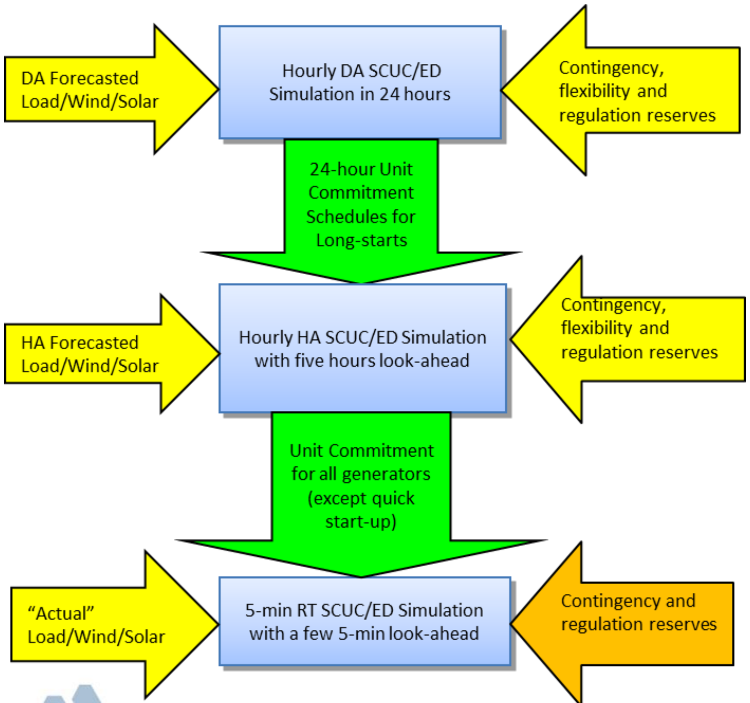
PSH Provides Load for RE Generation during Off-Peak Hours (Reduces RE Curtailments and Negative LMPs)



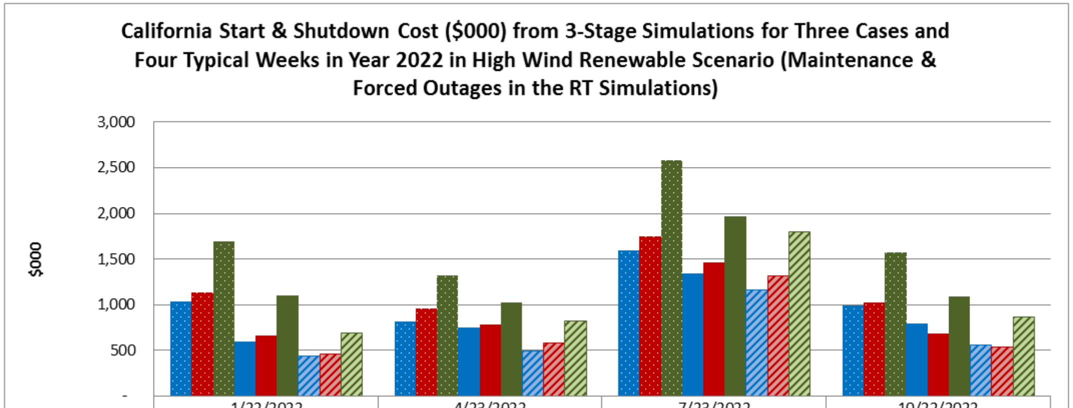
California: 3-Stage DA-HA-RT Modeling

- Detailed simulation (5-minute time step in RT simulations) of four typical weeks in different seasons of 2022 under High-Wind RE scenario
- Simulated: 3rd weeks of January, April, July, and October
- 3rd week in July is the peak load week

3-Stage Sequential Simulation



Results for Start and Shutdown Costs under High-Wind Scenario



	1/22/2022	4/23/2022	7/23/2022	10/22/2022
No PSH DA	1,032	821	1,595	990
No PSH HA	1,138	954	1,750	1,024
No PSH RT	1,690	1,320	2,580	1,575
FS PSH DA	595	753	1,344	799
FS PSH HA	667	781	1,468	686
FS PSH RT	1,104	1,027	1,973	1,085
FS&AS PSH DA	439	489	1,157	559
FS&AS PSH HA	464	578	1,313	541
FS&AS PSH RT	695	819	1,796	870

California: Summary of 3-Stage DA-HA-RT Modeling Results

Summary of 5-minute RT simulation results for High-Wind renewable generation scenario

High-Wind Renewable Scenario	Average Cost Savings or Decrease in Ramping Needs over the Four Simulated Typical Weeks in 2022			
	System Production Costs	Startup and Shutdown Costs	Ramp Up of Thermal Generators	Ramp Down of Thermal Generators
	%	%	%	%
No PSH	-	-	-	-
With FS PSH	5.01	27.58	9.76	15.10
With FS&AS PSH	7.27	41.67	33.05	64.16


Questions?
THANK YOU!